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Howard M. Resh

Hydroponic Food Production

A Definitive Guidebook for the Advanced Home Gardener and the Commercial Hydroponic Grower

EIGHTH EDITION

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Preface

The first edition of this book was published in 1978. Its last edition, the seventh, was revised in 2012. The eighth edition has undergone significant updates to keep it state of the art in the field of hydroponics. The author has maintained the book in its same format, but expanded many of the chapters and added two new chapters (Chapters 12 and 14) on greenhouse environmental control and vertical indoor farms. Also, updates on the sustainable yield concepts of hydroponics are discussed. The book is not highly technical in providing the basics of hydroponics in the initial chapters with regard to plant function and nutrition. The objective is to make the reader aware of the present advances in hydroponics using the various substrates and systems that have proved successful with specific vegetable crops. While most of the material presented relates to greenhouse hydroponic systems, it can be applied to outdoor hydroponic systems under favorable climates. This book is meant to be a practical guide for persons interested in entering hydroponics commercially or as a hobby. Whatever the size of operation the reader may be interested in, the book presents the principles for getting started and gives many examples and illustrations to clarify these methods.

The first four chapters introduce the reader to the history of hydroponics: plant nutrition, essential plant elements, nutrient uptake, nutritional disorders, sources of nutrients including organics, and then a detailed explanation of composing nutrient solutions. Sources of the nutrients are given with conversion tables to facilitate the calculations of nutrients the plant requires to the volumes of nutrient solution makeup. A new section on organic fertilizers has been added exemplifying sources and possible organic nutrient formulations. Concentrated nutrient stock solutions are explained and calculations are clearly exemplified. Many nutrient formulations are given as a reference to start the formulation for specific crops that can be optimized for specific conditions with experience. Various media or substrates most suitable to hydroponics or "soilless culture" are presented to explain their characteristics and assist the reader in choosing the best for his or her specific crop and growing system.

In Chapter 5, water culture systems are explained and illustrated. This includes raft or floating systems on a relatively small scale to large commercial operations. This section contains new material on commercial raceway or raft culture. Information on new commercial green fodder production has been added. Alfalfa and bean sprout production is presented to demonstrate the principles of growing sprouts. Production of microgreens includes both commercial and a do-it-yourself method so that one can easily set up such a system in the residence.

Chapter 6 on nutrient film technique (NFT) expands this culture to the most up-to-date automated systems presently in operation in Europe and North America. This section includes automated baby leaf greens production systems. A new section has been added to the commercial application of an A-frame NFT system growing strawberries in Australia that demonstrates marketing through a restaurant-retail outlet.

Chapters 7 through 9 on gravel, sand, and sawdust cultures, respectively, demonstrate growing systems with irrigation designs.

Chapter 10 on rockwool culture presents commercial state-of-the-art greenhouse operations. Recirculation of the nutrient solution is exemplified with rockwool culture through the use of raised beds. This recirculation of nutrient solution demonstrates the industry is reducing the environmental impact and supports the "green" concept toward the environment. Presented are examples and details of growing the main vine crops of cucumbers, tomatoes, and peppers with rockwool culture. Intercropping of tomatoes in high light regions, such as southern California, Arizona, and Australia are presented.

Chapter 11 on coco coir discusses the sources, grades, and characteristics of coco coir with the available products of cubes, blocks, and slabs that are used in this system. Greenhouse culture is moving toward such sustainable substrates to utilize normal waste products from other industries. Coco coir is such a substrate, similar to the case with sawdust culture in British Columbia, Canada some years ago as illustrated in Chapter 9. Sawdust later was used in manufactured wood products, so now is not readily available. Details of growing tomatoes with coco coir substrate are given.

Chapter 12 is a new chapter to explain the control of environmental factors in greenhouses. It also includes automation in greenhouses to perform daily tasks because of the increasing difficulty of acquiring labor. Temperature control through heating, ventilation and cooling, and polyclima (Ultra Clima, Modulair) systems in sustainable agriculture greenhouse technology are discussed. Combined heat and power (CHP) and cogeneration as part of sustainable greenhouses are presented. Carbon dioxide enrichment principles and generation systems are presented. Relative humidity (RH) and irrigation (fertigation) principles and techniques are given including recirculation of the nutrient solution with components of filtration, sterilization, and injection systems. Lighting principles and sources of lights including high intensity discharge (HID) and LED lighting units are presented.

Computer automation of greenhouse environmental factors and automation of crop production tasks from sowing, transplanting, plant training, harvesting, and packing are reviewed with examples of robotics being tested for crop harvesting. Retractable roof structures for protection of cherries is widely used to get earlier production, to increase yields, facilitate harvesting by new training systems are gaining popularity as the economics are proven. These same structures have advantages over closed greenhouses in tropical, humid climates in Australia, South Africa, Mexico, and the Middle East in growing normal greenhouse crops such as tomatoes, strawberries, lettuce, herbs, and cannabis.

Chapter 13 dealing with other soilless cultures covers the use of rice hulls, peatlite, and perlite cultures. The section on perlite culture has been expanded to elaborate on perlite products such as blocks and slabs and to include culture of eggplants using perlite.

Chapter 14 describing vertical indoor farming (VF) is new. It begins with some background on early vertical greenhouse and sack culture growing systems. From there present vertical growing systems used in greenhouses are described followed by existing commercial vertical greenhouses. Vertical indoor farming reviews many different systems by numerous companies where growing is in large warehouses with tiers of shelving growing lettuce, leafy greens, and herbs under LED lighting. Automation in these vertical farms is presented with each specific system. Vertical growing in containers and/or modular units is discussed. The chapter is summarized by advantages and disadvantages of these vertical farms with final remarks on their potential.

In Chapter 15 new sections have been added on Peru hydroponics describing the work at the Universidad Nacional Agraria La Molina and the large commercial operation of Invernaderos Hidroponias del Peru, near Lima, Peru. "Special Applications" has been updated to include the expansion of hydroponic rooftop greenhouses. New locations are described in New York, Chicago, and Montreal, Canada. Educational applications of hydroponics in school rooftop hydroponic gardens and the public display on the Hudson River in New York of the Science Barge are described.

Plant cultural techniques of Chapter 16 illustrates the training of plants, growing of seedlings, varieties, pest and disease management using integrated pest management (IPM). Eggplant culture is included with these cropping techniques. Green grafting of vine crops is now standard practice for tomatoes, peppers, and eggplants to mitigate crop diseases and increase yields. This is explained in detail using illustrations.

Included in Appendices are websites for all of the hydroponic and greenhouse resources and supplies to make access to them readily available.

Howard M. Resh

Acknowledgments

This book is based on over 43 years of personal working experience, visits with many growers, discussions with researchers and growers at conferences, and participation in many conferences such as the Asociacion Hidroponica Mexicana, A.C.; Centro Nacional de Jardineria Corazon Verde, Costa Rica; Encontro Brasileiro de Hidroponia, Brazil; Greenhouse Crop Production and Engineering Design Short Course, University of Arizona, CEAC; Hydroponic Society of America; International Society of Soilless Culture; and the Research Center for Hydroponics and Mineral Nutrition, Universidad Nacional Agraria, La Molina, Lima, Peru. Much appreciated thanks to the organizers of these conferences including: Gloria Samperio Ruiz, the late Laura Perez, Dr. Pedro Ferlani, Dr. Gene Giacomelli, and Dr. Alfredo Rodriguez Delfin

In addition, some information has been acquired over the years from numerous sources from books, scientific journals, and government publications whose recognition is given in the references following each chapter and in the general bibliography.

Special thanks to Dr. Silvio Velandia of Hidroponias Venezolanas C.A. of Caracas, Venezuela, for the hospitality and inspiration given to me during our association over the years in developing his hydroponic farm. He gave me the opportunity to gain experience in tropical hydroponics and encouraged me to write a chapter about it.

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My sincere gratitude to all of these people who are furthering the advances of hydroponics in greenhouse and indoor farming technologies.

In no way is the use of trade names intended to imply approval of any particular source or brand name over other similar ones not mentioned in this book.

–The Author

Author Bio

Howard M. Resh (born January 11, 1941) is a recognized authority worldwide on hydroponics. His website: www.howardresh.com presents information on hydroponic culture of various vegetable crops. In addition, he has written six books on hydroponic culture both for commercial growers and backyard hobbyists. While a graduate student at the University of British Columbia, in Vancouver, Canada in 1971, he was asked by a private group to assist them in the construction of hydroponic greenhouses in the Vancouver area. He continued with outside work in greenhouses and soon was asked to conduct evening extension courses in hydroponics.

Upon graduation with his doctorate degree in Horticulture in 1975 he became Urban Horticulturist for the faculty of plant science at the University of B.C. He held that position for three years before the call of commercial hydroponics took him to many projects in countries such as Venezuela, Taiwan, Saudi Arabia, the United States, and in 1999 to Anguilla, British West Indies, in the Eastern Caribbean.

While in the position of urban horticulturist, Resh taught courses in horticulture, hydroponics, plant propagation, greenhouse design, and production. During this period, while he was urban horticulturist and later general manager for a large plant nursery, he continued doing research and production consultation for a commercial hydroponic farm growing lettuce, watercress, and other vegetables in Venezuela. Later, during the period 1995–1996, Resh became project manager for the Venezuelan farm to develop hydroponic culture of lettuce, watercress, peppers, tomatoes, and European cucumbers using a special medium of rice hulls and coco coir from local sources. He also designed and constructed a mung bean and alfalfa sprout facility to introduce sprouts into the local market.

In the late 1980s, Resh worked with a company in Florida in the growing of lettuce in a floating raft culture system.

From 1990 to 1999, Resh worked as the technical director and project manager for hydroponic projects in the growing of watercress and herbs in California. He designed and constructed several 3-acre outdoor hydroponic watercress facilities using a unique NFT system. These overcame production losses due to drought conditions in the area.

From there in mid-1999, Resh became the hydroponic greenhouse farm manager for the first hydroponic farm associated with a high-end resort, CuisinArt Golf Resort & Spa, in Anguilla, British West Indies in the northeastern Caribbean. The hydroponic farm is unique in being the only one in the world owned by a resort growing its own fresh salad crops and herbs exclusively for the resort. This farm has become a key component of the resort in attracting guests to experience real homegrown types of vegetables, including tomatoes, cucumbers, peppers, eggplants, lettuce, bok choy, and herbs. The resort, together with its hydroponic farm, has gained world-wide recognition as one of the leading hotels of the world.

Resh continues to do consulting on many unique hydroponic greenhouse operations such as Lufa Farms in Montreal, Canada. There he established the growing techniques and hydroponic systems for a rooftop hydroponic greenhouse in downtown Montreal. All vegetables are marketed through a community supported agriculture (CSA) program.

In 2016, Resh retired from full-time work at CuisinArt Golf Resort & Spa and now independently consults with a number of companies including work on indoor vertical farming.

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1 Introduction

1.1 THE PAST

While hydroponics is a fairly recent term for growing plants without soil, the method dates back much earlier. The hanging gardens of Babylon, the floating gardens of the Aztecs of Mexico, and those of the Chinese were a form of "hydroponic" culture, although not referred to as that. Even Egyptian hieroglyphic records of several hundred years B.C. describe the growing of plants in water. Theophrastus (372–287 B.C.) undertook various experiments in crop nutrition. Botanical studies by Dioscorides date back to the first century A.D.

The earliest recorded scientific approach to discover plant constituents was in 1600 when Belgian Jan van Helmont showed in his classical experiment that plants obtain substances from water. While his conclusion that plants obtain substances for growth from water was correct, he failed to realize that they also require carbon dioxide and oxygen from the air. In 1699, an Englishman, John Woodward, grew plants in water containing various types of soil and found that the greatest growth occurred in water which contained the most soil. He thereby concluded that plant growth was a result of certain substances in the water, derived from soil, rather than simply from water itself.

Further progress in identifying these substances was slow until more sophisticated research techniques were developed and advances were made in the field of chemistry. In 1804, De Saussure proposed that plants are composed of chemical elements obtained from water, soil, and air. This proposition was verified later in 1851 by Boussingault, a French chemist, in his experiments with plants grown in sand, quartz, and charcoal, to which were added solutions of known chemical composition. He concluded that water was essential for plant growth in providing hydrogen and that plant dry matter consisted of hydrogen plus carbon and oxygen, which came from the air. He also stated that plants contain nitrogen and other mineral elements.

Researchers had demonstrated by that time that plants could be grown in an inert medium moistened with a water solution containing minerals required by the plants. The next step was to eliminate the medium entirely and grow the plants in a water solution containing these minerals. This was accomplished in 1860–1861 by two German scientists, Sachs and Knop. This was the origin of "nutriculture," and similar techniques are still used today in laboratory studies of plant physiology and plant nutrition. These early investigations in plant nutrition demonstrated that normal plant growth can be achieved by immersing the roots of a plant in a water solution containing salts of nitrogen (N), phosphorus (P), sulfur (S), potassium (K), calcium (Ca), and magnesium (Mg), which are now defined as the macroelements or macronutrients (elements required in relatively large amounts).

With further refinements in laboratory techniques and chemistry, scientists discovered seven elements required by plants in relatively small quantities – the microelements or trace elements. These include iron (Fe), chlorine (Cl), manganese (Mn), boron (B), zinc (Zn), copper (Cu), and molybdenum (Mo).

In the following years, researchers developed many diverse basic formulae for the study of plant nutrition. Some of these workers were Arnon, Hoagland, Robbins, Shive, Tollens, Tottingham, and Trelease. Many of their formulae are still used in laboratory research on plant nutrition and physiology.

Interest in practical application of this "nutriculture" did not develop until about 1925 when the greenhouse industry expressed interest in its use. Greenhouse soils had to be replaced frequently to overcome problems of soil structure, fertility, and pests. As a result, research workers became aware of the potential use of nutriculture to replace conventional soil cultural methods. Between 1925 and

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1935, extensive development took place in modifying the laboratory techniques of nutriculture to large-scale crop production.

In the early 1930s, W.F. Gericke of the University of California put laboratory experiments in plant nutrition on a commercial scale. In doing so, he termed these nutriculture systems *hydroponics*. The word was derived from two Greek words – *hydro* ("water") and *ponos* ("labor") – literally "water working."

Hydroponics can be defined as the science of growing plants without the use of soil, but by the use of an inert medium, such as gravel, sand, peat, vermiculite, pumice, perlite, coco coir, sawdust, rice hulls, or other substrates, to which is added a nutrient solution containing all the essential elements needed by the plant for its normal growth and development. Since many hydroponic methods employ some type of medium it is often termed "*soilless culture*," while water culture alone would be true hydroponics.

Using hydroponics, Gericke grew vegetables, including root crops such as beets, radishes, carrots, and potatoes; cereal crops; fruits; ornamentals; and flowers. Using water culture in large tanks, he grew tomatoes to such heights that he had to harvest them with a ladder. The American press made many irrational claims, calling it the discovery of the century. After an unsettled period in which unscrupulous people tried to cash in on the idea by selling useless equipment, more practical research was done and hydroponics became established on a sound scientific basis in horticulture, with recognition of its two principal advantages, high crop yields and its special utility in nonarable regions of the world.

Gericke's application of hydroponics soon proved itself by providing food for troops stationed on nonarable islands in the Pacific in the early 1940s. In 1945, the US Air Force solved its problem of providing its personnel with fresh vegetables by practicing hydroponics on a large scale on the rocky islands normally incapable of producing such crops.

After World War II, the military command continued to use hydroponics. For example, the US Army established a 22-ha project at Chofu, Japan. The commercial use of hydroponics expanded throughout the world in the 1950s to such countries as Italy, Spain, France, England, Germany, Sweden, the USSR, and Israel.

1.2 THE PRESENT

With the development of plastics, hydroponics took another large step forward. Plastics freed growers from the costly construction associated with the concrete beds and tanks previously used. With the development of suitable pumps, time clocks, plastic plumbing, solenoid valves, and other equipment, the entire hydroponic system can now be computer automated, reducing both capital and operational costs. Many modern greenhouse operations now use automation in the moving of growing channels within the greenhouse and automated, robotic transplanting and harvesting. Such operations exist in Europe and the United States. Hortiplan is such a company from Belgium that engineers and manufactures nutrient film technique (NFT) water-culture systems for automation, used at present in Belgium, Holland, the United States, and other areas of the world. Similar moving gutter systems (MGS) are available from several other companies, such as Viemose DGS of Denmark and Green Automation of Finland. These systems are elaborated upon in Chapter 6.

Hydroponics has become a reality for greenhouse growers in virtually all climates. Large hydroponic installations exist throughout the world for the growing of both flowers and vegetables. Many hydroponic vegetable production greenhouses exist in the United States, Canada, and Mexico that are 50 acres or larger in area. Large US growers include Village Farms, L.P., with operations (seven partner growers) in Western Canada, with the majority in Delta, British Columbia (60 acres), and Fort Davis and Marfa, Texas (40 acres). They have six partner growers in Mexico and two partner growers in Pennsylvania, with a total of 315 acres. Kentucky-based AppHarvest has 60 acres of greenhouse production in Morehead, Kentucky. Houweling's Group has 130 acres of greenhouse production in California and 28 acres in Utah (expanding by 30 acres in 2021). In Canada greenhouses

larger than 50 acres include Houweling's Group, Delta, British Columbia; Windset Farms, Delta, British Columbia. Mastron Enterprises Ltd., Leamington, Ontario; Nature Fresh Farms, Leamington, Ontario; Pure Hothouse Foods Inc., Leamington, Ontario; and DiCiocco Farms, Leamington, Ontario; Great Northern Hydroponics, Leamington, Ontario; and Mucci Farms of Kingsville, Ontario.

1.2.1 North American Greenhouse Vegetable Industry

The following statistics indicate the expansion of the North American greenhouse vegetable industry. A similar growth has occurred in Europe, but here the focus is on North America. In 1998 the industry in British Columbia (B.C.) and Ontario, Canada was reported at 1140 acres (456 ha). The Ontario marketing board claimed that in 1999 there was more than 800 acres (320 ha) of greenhouse vegetables compared to 600 acres (240 ha) the previous year. In 1998 the British Columbia Ministry of Agriculture and Lands reported 310 acres (124 ha) of greenhouse vegetable production. This increased over the next four years by 2002 to 510 acres (204 ha). Statistics Canada reported for 2008 and 2009 respectively; there were 2775 acres (1110 ha) and 2852 acres (1141 ha).

The Government of Canada 2018 Statistical Overview of the Canadian Greenhouse Vegetable Industry reported 1735 ha (4285 acres) in Canada with the largest areas in Ontario and British Columbia at 1220 ha (3013 acres) and 314 ha (775 acres) respectively. Perhaps, the small increase in B.C. is due to some of the large operations, such as Village Farms having converted 10 ha (25 acres) of their vegetable production to cannabis growing in 2017.

The breakdown of Canada's hydroponic greenhouse vegetable production according to 2018 data from Agriculture and Agri-Food Canada is as follows: Tomato-659 ha (1628 acres); Pepper-561 ha (1386 acres); Cucumber-457 ha (1128 acres); Lettuce-22 ha (54 acres); Eggplants-11 ha (27 acres); Herbs and other vegetables-25 ha (62 acres) totaling 1736 ha or 4285 acres. These figures are broken down into the area per crop in Table 1.1.

Hydroponic (soilless) culture is used in growing the majority of greenhouse ornamentals. In North America (Canada, US, and Mexico) the average percentage of ornamental compared to vegetable greenhouse crops is 63% vs. 37% (Hickman, 2018) indicating that the area of hydroponic greenhouse growing is much larger than what is presented here for vegetables alone. The percentage of hydroponic ornamentals is even greater in other countries such as the Netherlands.

The latest figures for the US greenhouse area in 2017 were given by the US Census of Agriculture, 2017. Total greenhouse vegetable production was 1046 ha (2584 acres). Of this total, the area of tomatoes was 594 ha (1468 acres). There was no breakdown for the other crops. In 2015 greenhouse vegetable production in Mexico was 3676 ha (9084 acres) as published in *International Greenhouse Vegetable Production Statistics – 2018 Edition* by Gary W. Hickman. The total North American greenhouse vegetable production was reported to be 6396 ha or 15,883 acres.

Almost half of the greenhouse vegetable production area in the US is produced by ten companies. They have 435 ha (1078 acres) of the total production of 1046 ha (2584 acres) as reported in 2017. That is, they operate 42% of the greenhouse area in the US. The following is a list of these large greenhouse operations.

Nature Sweet (Desert Glory Ltd.) – 106 ha (262 acres) (AZ) (2017)
Winset Farms – 68 ha (168 acres) (CA) (2020)
Houweling's Group – 50 ha (124 acres) (CA) + 23 ha (58 acres) (UT) (2021)
Village Farms – 49 ha (122 acres) + 12 ha (30 acres) (TX) (2020)
Sunblest Farms – 36 ha (90 acres) (CO) (2000)
Intergrow – 38.5 ha (95 acres) (NY) (2019)
AppHarvest – 24.3 ha (60 acres) (KY) (2021)
Mastronardi Produce (Backyard Farms) – 17 ha (42 acres) (ME) (2017)
Mucci Farms – 20 ha (50 acres) (OH) (2020)
Nature Fresh Farms – 18 ha (45 acres) (OH) (2018)

TABLE 1.1
Greenhouse Vegetable Production Area, Canada 2017–2019

Province	Tomatoes Hectares (Acres)	Cucumbers Hectares (Acres)	Peppers Hectares (Acres)	Lettuce Hectares (Acres)	Eggplants Hectares (Acres)	Herbs Hectares (Acres)	*Other Hectares (Acres)	Totals Hectares (Acres)
				2017:				
British Columbia	108 (267)	44 (109)	155 (383)	4.3 (10.5)	1.5 (3.7)	6.3 (15.6)	2.9 (7.2)	322 (795)
Ontario	436 (1077)	322 (795)	395 (976)	4.5 (11)	8.3 (20.5)	0.3 (0.74)	2.2 (5.4)	1168 (2885)
Others	92 (227)	66 (163)	13 (32)	12 (30)	1.2 (3)	2.6 (6.4)	9 (22.2)	196 (484)
Canada	636 (1571)	432 (1067)	563 (1391)	21 (52)	11 (27)	9.1 (22.7)	14.1 (34.8)	1686 (4164)
				2018:				
British Columbia	104 (257)	45 (111)	148 (365)	5 (12)	1.4 (3.4)	4.2 (10.4)	6 (14.8)	314 (775)
Ontario	460 (1136)	343 (847)	400 (988)	5 (12)	8.7 (21.4)	0.34 (0.84)	2.9 (7.2)	1220 (3013)
Others	95 (235)	69 (170)	13 (34)	12 (30)	0.9 (2.2)	2.5 (6.2)	8.8 (21.7)	201 (497)
Canada	659 (1628)	457 (1128)	561 (1386)	22 (54)	11 (27)	7 (18)	17.7 (44)	1736 (4285)
				2019:				
British Columbia	96.3 (238)	45.7 (113)	144 (356)	5.4 (13)	1.2 (3)	7.6 (19)	2.8 (7)	303 (749)
Ontario	456 (1126)	368 (909)	399 (986)	6.7 (16.5)	8.4 (21)	0.4 (1)	1.1 (2.7)	1240 (3062)
Others	94 (232)	70.4 (174)	14 (34.5)	19.6 (48.4)	1.1 (2.7)	2.5 (6.2)	10.5 (26)	212 (524)
Canada	646.3 (1596)	484 (1196)	557 (1376)	31.7 (78)	10.7 (26.7)	10.5 (26.2)	14.4 (36)	1755 (4335)

*Other: Other Greenhouse Vegetable Crops – Chinese vegetables and leafy greens.

Source: Statistics Canada. Table 32-10-0456-01 Production and value of greenhouse vegetables

1.2.2 World Greenhouse Vegetable Industry

While there are many statistics reporting areas of greenhouse vegetable production throughout the world, it is important to recognize that often such statistics include all protective structures, such as high plastic tunnels, shade structures, and any structures that will extend the growing season of plants. Many of these are not greenhouses with environmental control systems such as heating, cooling, nutrient systems with drip irrigation, protection against pests, and other components to modify the internal environment to achieve optimal conditions for the crop grown. In addition, greenhouses in many countries may still use soil and not a soilless or hydroponic system.

A recent publication by Gary W. Hickman, *International Greenhouse Vegetable Production Statistics – 2018 Edition*, claims world soilless/hydroponic vegetable production is about 95,000 ha (235,000 acres). Hickman also points out that commercial greenhouse vegetable production is estimated at 498,000 ha (1.23 million acres).

Greenhouse hydroponic production must be considered as using a hydroponic system, not just covering the existing soil with a very lightweight poly structure such as poly tunnels and plastic low tunnels and applying water with some nutrients by a drip irrigation system, such as in areas like the Canary Islands, Spain, China, and Mexico. For example, Hickman points out that Mexico is producing about 3770 ha (9300 acres) of natural ventilated, unheated, high-tunnel structures of plastic covered metal structures with insect sidewalls. These "greenhouses" often have computerized irrigation and fertilization systems, but are growing in the local soil. As a result, they cannot be termed "hydroponic."

The largest Mexican hydroponic greenhouse operation is Bionatur Greenhouses in Jocotitlan, Mexico. They operate 200 acres or 80 ha growing tomatoes with 1000 employees. There are numerous other hydroponic greenhouse vegetable production facilities, such as Agros S.A. presently 17 ha or 42 acres in the state of Queretaro.

Holland, on the other hand, has 4865 ha (12,022 acres) of hydroponic vegetable production with sophisticated, high-technology greenhouses of metal and glass with computer-controlled environments. Other statistics report an area of 10,000 ha (25,000 acres), but that would include flower production. While Holland is still the largest, Spain now has about 4000 ha; however, the greenhouse structures there are much lower-cost polyethylene structures unlike most Dutch glass greenhouses. Belgium in 2007 had about 1430 ha (3530 acres). Germany in 2015 had about 1204 ha or 2975 acres according to statistics gathered by Hickman.

Further statistics presented by Hickman (2019) indicate in 2016 Australia greenhouse production was 500 ha (1230 Ac). NFT, rockwool and coco coir cultures are the principal hydroponic methods employed. The greater portion of hydroponic growers is located in New South Wales and Victoria.

Nichols and Christie (2008) reported in *Practical Hydroponics & Greenhouses* that, in 2007 Japan had 52,000 ha of greenhouses, mainly of plastic, with only 5% glass, but only 1500 ha (3%) were in a hydroponic system.

The largest growers in Australia include Costa Tomatoes in Guyra, NSW, with 30.2 ha (75 acres) presently expanding to 40 ha (99 acres). In Two Wells, near Adelaide, South Australia, d'VineRipe is located, which has 43 ha (106 acres). Flavorite in Warragul, Victoria, has 26 ha (64 acres), presently expanding by 4.5 ha (11 acres) for a total of 30.5 ha (75 acres). Sundrop Farms in Port Augusta, South Australia, has a 20-hectare (50-acre) greenhouse using a solar tower to produce energy for the greenhouse operation. These greenhouses grow principally tomatoes and peppers.

The largest greenhouse operation in New Zealand is NZ Hothouse, Drury, near Auckland. They have 20 ha (~50 acres) of Venlo glasshouses growing mainly tomatoes with some cucumbers in rockwool. They supply New Zealand supermarkets and export to Canada, the United States, Australia, Singapore, Japan, Taiwan, and Oceania.

Hydroponics is now used in almost every country in the world. Hickman, in his study of greenhouse vegetable production, reported information on 130 countries that produce greenhouse vegetables commercially. While the majority of this greenhouse vegetable production is in the soil, hydroponics is generally also part of this industry, even if on a smaller scale. Even countries such as Turkey in 2014 claim 65,000 ha (160,500 acres) of greenhouse production. As mentioned earlier, such as in the case of Spain and Mexico, a large part of that production would be in plastic tunnels and low-profile cold frames that may be misnamed greenhouses. Hickman (2019) reported almost 30,000 ha (74,100 acres) of this was plastic greenhouses with 8114 ha (20,042 acres) glass greenhouses. Their principal production is tomatoes, cucumbers, peppers, watermelons, and eggplants.

Greenhouse vegetable area in Russia, from statistics reported by Hickman (2018), had increased from 1840 ha (4547 acres) in 2012 to 2931 ha (7243 acres) in 2014.

TABLE 1.2
Large World Greenhouse Vegetable Operations

Country	Name	Hectares	Acres
Morocco	Group Azura	751	1856
Mexico	Desert Glory	405	1000
Mexico	Melones	350	865
China	Le Gaga	263	649
Mexico	Agricola la Primavera	162	400
Russia	Yuzhny	148	366
Canada	Petro Veg. Co.	135	334
Mexico	Divemex	135	334
Mexico	Bioparques de Occidente	130	321
Russia	Agrikombinat Moskovsky	120	300
Mexico	Grupo Batiz-Wilson Batiz	115	284
USA	Nature Sweet Arizona	106	265
Netherlands	Royal Pride	102	252
Israel	Gilad Desert Produce	100	250

In arid regions of the world, such as Mexico and the Middle East, hydroponic complexes combined with desalination units are being developed to use sea water as a source of fresh water. With less expensive desalination equipment, such as reverse osmosis (RO), water can be generated in these arid regions at an economically feasible cost for use in greenhouses. The complexes are located near the ocean and plants are often grown in the existing sand.

Global Greenhouse Vegetable Area-*By Continent 2017 (Compiled by Hickman, 2018)*

Europe	173,561 ha. (428,879 acres)
South America	12,502 ha. (30,893 acres)
North America	7,288 ha. (18,009 acres)
Asia	224,974 ha. (555,923 acres)
Africa	36,993 ha. (91,412 acres)
Oceania	2,036 ha. (5,031 acres)

Large world greenhouse vegetable operations (Table 1.2) are from numerous sources that were compiled by Hickman (2018).

This list of the largest greenhouse operations in the world may not all use hydroponic culture. Desert Glory, Petro Veg. Co., and Nature Sweet Farms use only hydroponic culture. The following list in Table 1.3 is the area of soilless or hydroponic culture in greenhouses in some countries.

1.3 THE FUTURE

In a relatively short period of time, over about 65 years, hydroponics has adapted to many situations, from outdoor field culture and indoor greenhouse culture to highly specialized culture in the space program. It is a space-age science, but at the same time can be used in developing countries of the Third World to provide intensive food production in limited area. Its only restraints are sources of fresh water and nutrients. In areas where fresh water is not available, hydroponics can use seawater through desalination. Therefore, it has potential application in providing food in areas having vast regions of nonarable land, such as deserts. Hydroponic operations can be located along coastal

TABLE 1.3
Soilless/Hydroponic Greenhouse Vegetable Production Area

Country	Hectares	Acres	
China	1,250	3,100	
Japan	1,500	3,700	
Turkey	500	1,235	
Italy	4,000	10,000	
Morocco	426	1,053	
Netherlands	4,600	11,300	(some area is not soilless)
Mexico	4,305	10,638	(some area is not soilless)
New Zealand	688	1,700	(95% is soilless culture)
U.S.A.	574	1,418	
United Kingdom	89	220	
South Africa	75	185	
Taiwan	35	86	
Singapore	30	74	
Canada	1,141	2,852	

Source: Gary W. Hickman, 2011, *Greenhouse Vegetable Production Statistics.*

regions in combination with petroleum-fueled, solar, or atomic desalination units, using the beach sand as the medium for growing the plants.

Hydroponics is a valuable culture to grow fresh vegetables in countries having little arable land and those that are very small in area yet have a large population. It could also be particularly useful in some smaller countries whose chief industry is tourism.

In such countries tourist facilities, such as resort hotels, can grow their own products instead of importing them many thousands of miles away, with long shipping periods. Typical examples of such regions are the West Indies and Hawaii, which have a large tourist industry and very little farm land in vegetable production.

Hydroponic greenhouse operations will be linked with industries having waste heat or alternative sources of energy. Such cogeneration projects already exist in California, Colorado, Nevada, Pennsylvania, and Utah. Anaerobic digesters of animal waste products can have hydroponic greenhouses associated with them in the Midwest where lots of dairy farms exist. The anaerobic digesters can generate heat and electricity. Electric power generating stations use water in their cooling towers. This heated water can be used both for heating the greenhouse and providing distilled water free of minerals for the growing of plants in recirculation systems. This clean water is of particular advantage to growers in areas normally having hard raw water. In most of the sun-belt locations where sunlight is favorable to high production of vegetables, waters are very hard with high levels of minerals, which are often in excess of normal plant requirements. The hard water also creates problems with corrosion of equipment, plugging of cooling pads, fogging systems, and structural breakdown of growing media.

With the introduction of new technology in artificial lighting, the growing of plants using artificial lighting will become economically feasible, especially in the more northern latitudes where sunlight is limited during the year, from late fall to early spring. During this period, of course, the prices for produce are much higher than in summer months. The new LED lights have this potential. Heat generated from the lights could be used to supplement the heating of the growing operation.

There are many locations in western North America having geothermal sources of heat. Such sites exist in Alaska, California, Colorado, Idaho, Montana, Oregon, Utah, Washington, Wyoming,

and British Columbia. In the future, large greenhouses should be located close to geothermal sites to utilize the heat, as is presently done in Hokkaido, Japan.

At present, a lot of research is being carried out to develop hydroponic systems for the growing of vegetables on the space station. Closed-loop recirculation systems are being designed and tested to operate under microgravity (very low gravity) environments. Such hydroponic systems will grow food to nourish astronauts on long space missions.

In large cities where fresh vegetables are transported often long distances from their growing facilities, there is potential for hydroponic greenhouse roof-top gardens. In a recent issue of *Scientific American* (November 2009), an article was written by Despommier (2009) describing how vertical high-rise buildings of 30 stories could grow produce within our large cities. Hydroponic systems would be used in conjunction with solar cells and incineration of plant waste to create power, and treated wastewater from the city would irrigate the plants. Sunlight and artificial lighting would provide light.

The most recent commercial development over the past ten years is the growing of commercial vegetable crops in *Indoor Vertical Farms* (VF). This is being termed the future of vegetable production within large cities or nearby in urban areas. These VFs now exist in North America, Europe, Middle East, Southeast Asia, Japan, Taiwan, and China. Vertical farms are discussed in Chapter 14.

1.4 SUITABLE SITE CHARACTERISTICS

When considering a hydroponic greenhouse site location, try to meet as many of the following requirements as possible to improve success.

1. In northern latitudes, a site that has full east, south, and west exposure to sunlight with a windbreak on the north.
2. An area that is as near level as possible or one that can be easily leveled.
3. Good internal drainage with minimum percolation rate of 1 in./h.
4. Availability of natural gas, three-phase electricity, telephone, and good-quality water, with capability to supply at least one-half gallon of water per plant per day. If the raw water is high in salts, an RO desalination unit will be needed.
5. Location on or near a main road close to a population center for wholesale market and retail market at the greenhouses if one chooses to sell retail.
6. Location close to residence for ease of checking the greenhouse during extremes of weather. All modern computer-controlled greenhouses have alarm and call-up systems to alert the grower. Parameters can also be checked through a laptop computer or mobile phone.
7. North–south oriented greenhouses with rows also north–south in northern latitudes.
8. A region that has a maximum amount of sunlight.
9. Areas not having excessive strong winds.
10. Areas that are not of high water table or in a flood plain. Fill would be required in such areas, which will add to capital costs.

1.5 SOIL VERSUS SOILLESS CULTURE

The large increases in yields under hydroponic culture over that of soil may be due to several factors. In some cases, the soil may lack nutrients and have poor structure; therefore, soilless culture would be very beneficial. The presence of pests or diseases in the soils greatly reduces overall production. Under greenhouse conditions, when environmental conditions other than the medium are similar for both soil and soilless culture, the increased production of tomatoes grown hydroponically is usually

TABLE 1.4
Advantages of Soilless Culture versus Soil Culture

Cultural Practice	Soil Culture	Soilless Culture
Sterilization of growing medium	Steam, chemical fumigants; labor intensive; time required is lengthy; minimum 2–3 wk	Steam, chemical fumigants with some systems; others can use bleach or HCl; short time needed to sterilize
Plant nutrition	Highly variable, localized deficiencies: often unavailable to plants because of poor soil structure or *p*H; unstable conditions; difficult to sample, test, and adjust	Controlled; relatively stable; homogeneous to all plants; readily available in sufficient quantities; good control of *p*H; easily tested, sampled, and adjusted
Plant spacing	Limited by soil nutrition and available light	Limited only by available light; making closer spacing possible; increased number of plants per unit area, resulting in more efficient use of space and greater yields per unit area
Weed control cultivation	Weeds present, cultivate regularly	No weeds, no cultivation
Diseases and soil inhabitants	Many soil-borne diseases, nematodes, insects, and animals, which can attack crops; frequent use of crop rotation to overcome buildup of infestation	No diseases, insects, animals in medium; no need for crop rotation
Water	Plants often subjected to water stress because of poor soil-water relations, soil structure, and low water-holding capacity. Saline waters cannot be used. Inefficient use of water; much is lost as deep percolation past the plant root zone and also by evaporation from the soil surface	No water stress. Complete automation by use of moisture-sensing devices and a feedback mechanism. Reduces labor costs, can use relatively high saline waters, efficient water use, no loss of water to percolation beyond root zone or surface evaporation; if managed properly, water loss should equal transpirational loss
Fruit quality	Often fruit is soft or puffy because of potassium and calcium deficiencies. This results in poor shelf life	Fruit is firm, with long shelf life. This enables growers to pick vine-ripened fruit and ship it long distances. In addition, little, if any, spoilage occurs at the supermarket. Some tests have shown higher Vitamin A content in hydroponically grown tomatoes than in those grown in soil
Fertilizers	Use large quantities over the soil, nonuniform distribution to plants, large amount leached past plant root zone (50–80%), inefficient use	Use small quantities, uniformly distributed to all plants, no leaching beyond root zone, efficient use
Sanitation	Organic wastes used as fertilizers onto edible portions of plants cause many human diseases	No biological agents added to nutrients; no human disease organisms present on plants

(*continued*)

TABLE 1.4 (Continued)
Advantages of Soilless Culture versus Soil Culture

Cultural Practice	Soil Culture	Soilless Culture
Transplanting	Need to prepare soil, uproot plants, which leads to transplanting shock. Difficult to control soil temperatures and disease organisms, which may retard or kill transplants	No preparation of medium required before transplanting; transplanting shock minimized, faster "take" and subsequent growth. Medium temperature can be maintained optimum. No disease present
Plant maturity	Often slowed by non-optimum conditions	With adequate light conditions, plant can mature faster under a soilless system than in soil
Permanence	Soil in a greenhouse must be changed regularly every several years since fertility and structure break down	No need to change medium in gravel, sand, or water cultures; no need to fallow. Sawdust, peat, coco coir, vermiculite, perlite, rockwool may last for several years between changes with sterilization
Yields	Greenhouse tomatoes 15–20 lb/yr/plant	Greenhouse tomatoes 50–70 lb/yr/plant

20–25%. Such greenhouses practice soil sterilization and use adequate fertilizers; as a result, many of the problems encountered under field conditions in soil would be overcome. This would account for the smaller increases in yields obtained by soilless culture under greenhouse conditions over the very striking 4–10 times increase in yields obtained by soilless culture outdoors over conventional soil-grown conditions.

Specific greenhouse varieties have been bred to produce higher yields under greenhouse culture than field-grown varieties could under the same conditions. These greenhouse varieties cannot tolerate the daily temperature fluctuations of outdoor culture; therefore, their use is restricted to greenhouse growing. Nonetheless, given optimum growing conditions of hydroponic greenhouse culture, they will far out-yield field varieties. The principal vegetable crops grown in hydroponic greenhouse culture include tomatoes, cucumbers, peppers, eggplants, lettuce and other leafy greens and herbs.

These greenhouse varieties have also been bred to resist or tolerate diseases of the foliage and roots, thereby increasing production. Now rootstocks are green grafted to tomatoes, peppers, and eggplants. The tomato root stock is more vigorous than the scion (commercial variety) and resists root diseases.

The main disadvantages of hydroponics are the high initial capital cost; some diseases caused by organisms such as *Fusarium* and *Verticillium*, which can spread rapidly through the system; and the complex nutritional problems encountered. Most of these disadvantages can be overcome by rootstocks, new varieties having more disease resistance, and better nutrient testing, devices.

Overall, the main advantages of hydroponics over soil culture are more efficient nutrition regulation, availability in regions of the world having nonarable land, efficient use of water and fertilizers, ease and low cost of sterilization of the medium, and higher-density planting, leading to increased yields per acre (Table 1.4).

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